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ELECTRONICS RESEARCH LABORATORY

STANFORD UNIVERSITY

CALIFORNIA

AN EXPERIMENTAL ANALYSIS OF SIGNAL INTERCEPTION BY RAPID-SCAN MICROWAVE RECEIVERS

By

G. DETHLEFSEN

TECHNICAL REPORT NO. 13

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BY RAPID SCAN MICROWAVE RECEIVERS.

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Douglas G. Dethlefsen

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ABSTRACT

This report is concerned with an experimental evaluation of the probability of interception of a pulsed radar signal by periodically tuned intercept receivers.

The problem has been attacked by simulating the radar transmitter and intercept receiver characteristics with electronic equipments providing pulse trains representing (1) the time interval during which the radar transmission is directed toward the receiver, and (2) the time interval during which an intercept receiver employing a directional receiving antenna is responsive to the incoming radar transmission. An interception of a radar transmission by the receiver is indicated by a finite time coincidence of these pulse trains. By a method of counting the pulses actually appearing in the simulated receiver circuits, the effectiveness of the operation is measured by determining both the time distribution and percentage of radar pulses intercepted.

Particular attention has been devoted to the case of the so-called rapid-scan receiver (scan rates greater than a few per second) and design recommendations are made regarding receiver scan rate and acceptance band.

The acceptance band of the receiver is a particularly important design parameter. On a long-term average, the percentage of radar pulses intercepted out of the total number

of radar pulses directed toward the receiver is equal to the ratio of the receiver acceptance band to the total rf spectrum scanned.

With a given acceptance band, a minimum receiver scan rate exists below which there is an increasing probability of intercepting no radar pulses from a particular radar pulse train. Above this limit (and with a suitable acceptance band), a more desirable condition exists; in the absence of synchronism between radar pulse repetition rate and intercept receiver scan rate, some pulses from each radar pulse train will be intercepted, thereby insuring good intercept probability. For many receivers, a range of scan rate exists in which complete synchronism is impossible. In any event, the effects of synchronism can be relieved by introducing a time "jitter" in the intercept receiver frequency scan.

The introduction of a rotating directional receiving antenna reduces the long-term average percentage of intercepted radar pulses by a factor equal to the effective beam width of the receiving antenna divided by 360. Practically, this reduces intercept probability in a number of important situations to unacceptable values. A method of direction-finding with a rotating antenna and rapid-scan receiver is evaluated in which the direction-finding function is time-shared with the normal search operation conducted with an

omnidirectional receiving antenna. It appears that the direction-finding operation often can be accomplished satisfactorily thereby and for little loss in efficiency of initial signal interception.

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CHAPTER I

INTRODUCTION: THE INTERCEPT PROBLEM

An important phase of radar countermeasures involves the determination of radar signal frequencies and general characteristics, and geographical locations of the radar units. The search for unknown radar signals (which presumably can appear at any time within a wide portion of the rf spectrum) is made with radar intercept receivers. These receivers are usually designed to monitor a wide frequency range. Frequently, they are able to do so only with some sacrifice in the probability of intercepting a signal on any particular frequency in a short time -- this loss of search efficiency is undesirable from the operational point of view. This report is concerned with the effect on intercept probability of a number of important receiving system parameters.

There are three basic intercept receiver types which may be differentiated by the nature of their normal tuning process.

1. The non-scan receiver incorporates no periodic tuning process. It is always sensitive to signals at any frequency within its range. The monitored rf

spectrum of such receivers is normally smaller than comparable scanning receivers. A number of types are under development in several laboratories.

2. The slow-scan receiver (usually several seconds per scan) has developed through the addition of automatic tuning mechanisms (usually mechanical) to conventional intercept receivers. A number of such receivers are in existence. They feature high sensitivity, and excellent selectivity is gained through narrow acceptance bands.

3. The rapid-scan receivers (scan rates of the order of a few scans per second to thousands per second) are, in some types, based on mechanical tuning mechanisms and, in other types, on electronic methods. There are wide variations in sensitivity and selectivity depending upon intended use.

Slow-scan receivers have been in existence for a number of years and are the most highly developed type. The intercept problems attendant to their use have been the subject for a large number of theoretical and a few experimental investigations. A recent theoretical work, applicable to both slow-scan

and rapid-scan receivers was conducted at Stanford University by Major Allen R. Matthews, USAF.[1] Some of the experimental work covered in this report is in the nature of a verification of portions of that project.

Recent electronic developments have resulted in several practical rapid-scan receivers. The potential characteristics of such equipments are such as to modify the problem of intercept probability in a number of important aspects. The work reported herein is concerned primarily with rapid-scan receivers although the principal relationships developed are general in nature.

The scanning intercept receiver tunes periodically across a given frequency band in an effort to determine the presence and radio frequency of a radar transmission. The periodic tuning process (frequency scanning) enables a receiver of limited acceptance band (the frequency bandwidth over which the receiver is instantaneously sensitive) to monitor an rf spectrum many times wider. This is accomplished only with some sacrifices in intercept probability, for the receiver is receptive to a signal on any given frequency only for short periodic time

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[1] Allen R. Matthews, An Analysis of Desirable Operational Characteristics of Microwave Intercept Receivers. (A thesis). Stanford University, 1951. This report lists a number of references to other investigations of intercept probability.

intervals; the radar transmission available at the receiving antenna is also discontinuous in time due both to the pulsed nature of the transmission and to the rotation of the directional radar antenna.[2] A finite time coincidence between these unrelated intervals is required for an intercept by the receiver.

An important problem and one which is the concern of this report, is the selection of receiver parameters to maximize the probability of intercepting a radar transmission in an operationally short time. A second problem, also considered herein, arises if a rotating directional receiving antenna is employed with the receiver in order to establish the bearing of the radar transmitter from the intercept receiver. Such an antenna acts as another "time gate" limiting the opportunities to intercept a signal, for the receiving antenna beam passes through the bearing of the radar only for short periodic time intervals.

There are, then, either two or three effective time gates which reduce the probability of intercepting a radar signal:

a. the scanning (in azimuth) of the directional radar antenna,

b. the scanning (in frequency) of the intercept receiver, and

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[2]Each time interval during which the radar system is directing its main-lobe signal toward the receiver is sometimes termed a "look" by the radar. One radar "look" occurs per revolution of the radar directional antenna. The time duration of a radar look is given by

$$\text{Look (Seconds)} = \frac{\text{Antenna Beam Width (Degrees)}}{\text{Antenna Rotation Rate (RPM)} \times 6}.$$

c. the scanning (in azimuth) of the direction-finding receiving antenna, if used.

The first factor ceases to be an effective time gate if the receiver is sufficiently sensitive to detect appreciable minor-lobe radiation from the radar antenna, producing thereby, a practically continuous intercepted radar signal in the receiver. Several modern receivers (usually of the slow-scan type) exhibit sensitivity of the required order of magnitude and have achieved at least a partial solution to certain practical intercept probability problems thereby. The more usual situation and the more difficult problem as regards intercept probability involves a less sensitive receiver, and this is the situation to be considered here.

The characteristics of the radar transmission are beyond the control of the intercept system. Included among these characteristics are not only the pulse repetition rate and pulse width of the radar transmission but, more important, the extent and timing of the periodic transmissions of radar pulses available at the receiving point (the radar look).

The second and third factors are under the control of the receiver designer and the influence on intercept probability of the following four important receiver design parameters are considered in this report:

1. receiver scan rate,
2. receiver acceptance band,

3. receiver direction-finding antenna beam width, and

4. receiver direction-finding antenna rotation rate.

(1) and (2) of these parameters relate to the second factor, (b), while (3) and (4) relate to the third factor, (c).

The presence of a radar transmitter is evidenced at the intercept receiver by momentary, usually periodic, groups of short pulses.[3] In this experiment, the effects of the various receiver equipment design parameters have been measured by determining the percentage of these radar pulses available at the receiving antenna which actually appear in the receiver circuits.

Some caution must be observed in the interpretation of results, for both the intercepted percentage and the time distribution of intercepted pulses are important. A receiving system which intercepts all pulses of one radar look and then intercepts no pulses during several successive looks would not be as desirable as one which intercepts a few pulses during each radar look (though the long-term average percentage of intercepted radar pulses might be the same in the two cases).

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[3]Characteristically, the duration of a radar pulse is short both in time (perhaps 1.0 microsecond) and relative to the interval between pulses, duty cycles of 0.001 being common. Similarly, the duration of pulse groups is short. A pulse group may cover an interval of the order of 1/20 second, and the time interval between such groups might be of the order of 10 seconds.

Similarly, a system which intercepted pulses on all radar looks but only one pulse in each might not be satisfactory, this being due to the practical difficulty of distinguishing a single radar pulse from the random noise pulses always present in a sensitive system. The ability of a human observer (or an electronic equipment) to detect the presence of a radar transmission in the receiver circuits improves tremendously with an increase in the number of radar pulses intercepted during any one radar look; the periodic nature of the radar pulses readily distinguishes them from the random noise pulses.

CHAPTER II

ELECTRONIC SIMULATION OF THE INTERCEPT PROBLEM

A. Simulation of Variables

This problem has been attacked by the method of simulation. Equipment was constructed to simulate the variables of the problem, combine them in their proper relation to the problem, and provide the desired information in the form of numbers of radar pulses intercepted under a specified set of conditions. This information will be a function of the following eight variables:

Transmitter Pulse Repetition Rate
Transmitter Pulse Width
Transmitter Antenna Beam Width
Transmitter Antenna Rotation Rate
Receiver Scan Rate
Receiver Acceptance Band
Receiver Antenna Beam Width
Receiver Antenna Rotation Rate

Receiver scan rate is defined as the frequency at which the intercept receiver scans through the frequency spectrum being searched. Receiver acceptance band is defined as the frequency bandwidth over which the receiver is instantaneously sensitive to incoming pulses from the radar transmitter. The acceptance

band will normally be a small fraction of the total rf spectrum scanned. The other variables are self-explanatory.

The problem was divided into two parts; first, the determination of data under the condition of the receiver employing an omnidirectional receiving antenna, and second, the determination of data under the condition of the receiver employing directional antennas of different beam widths and rotation rates.

The several parameters controlling the intercept can be represented by time functions in the simulator. The gating effect of the receiver frequency scan, for example, can be represented by periodic time intervals related to the passage of the acceptance band through a signal frequency. In the resulting pulse train, pulse repetition period is related to receiver scan period and pulse width to the ratio, $\frac{\text{Acceptance Band (mc)}}{\text{Frequency Scan (mc/sec.)}}$.

The simulation of the antenna parameters of beam width and rotation rate is accomplished identically for either rotating antenna. The radar antenna simulation will be used as an example. As the antenna rotates, the main lobe of its radiation pattern will cross the azimuthal line from the radar to the receiver. There will be two points in this pattern, one on either side of center, between which the signal will be of sufficient amplitude to be detected by the receiver. The time interval between the intersections of these two points with the azimuthal line from transmitter to receiver denotes the time during which the receiver is responsive to the radiated energy

from the transmitter. This time interval is a direct function of the transmitter antenna beam width and rotation rate and is equal to their ratio, $\frac{\text{Beam Width (Degrees)}}{\text{Rotation Rate (Degrees/Unit Time)}}$. Hence, these antenna parameters may be simulated by a pulse train whose pulse repetition period corresponds to antenna rotation period and whose pulse width corresponds to the ratio, $\frac{\text{Beam Width}}{\text{Rotation Rate}}$.

In this manner, one pulse train is used to simulate the transmitter antenna parameters and another to simulate the intercept receiver antenna parameters.

The transmitter simulation is completed by using the antenna "pulse" to gate through a series of pulses representative of the pulse repetition rate and pulse width characteristics of the selected radar transmitter. The receiver simulation is completed by using the receiver antenna pulse (in effect, a continuous signal if an omnidirectional receiving antenna is assumed) to gate through the pulse train representative of the time intervals during which the receiver is receptive to the signal frequency.

The time coincidence required for an actual interception is simulated by a coincidence of the several pulse trains.

A major assumption made in the experiments is that the coincidence problem can be simulated with pulse trains consisting of rectangular pulses. No account is taken of signal amplitude variations in the receiver during a coincidence

period (these variations being due to receiver pass-band response and antenna patterns). It is assumed only that there will be a continuous time interval lasting through any one coincidence during which the signal will be above the minimum detectable amplitude. In the examples, substituted limits are characteristic of the 3db widths of receiver pass-band response and antenna beam patterns. It must be remembered that these values (and the experimental results) will represent the intercept situation accurately only for specific combinations of radar power, effective antenna beam width, receiver sensitivity, range from receiver to radar transmitter, etc. A significant decrease in range, for example, could widen the coincidence period and improve intercept probability. A significant range increase might completely eliminate the possibility of a practical intercept even though a time coincidence in antenna directions and equipment timing existed.

B. Operation of Simulator

The simulator is outlined in block diagram form in Figure No. 1. The portions of the device designed to simulate the radar transmitter and receiving system are enclosed in separate dotted-line blocks.[1]

The radar transmitter pulse repetition rate is simulated by an astable multivibrator. The output trigger pulses from this circuit trigger a monostable multivibrator whose delay

[1]Circuit details of the simulator are given in the Appendix.

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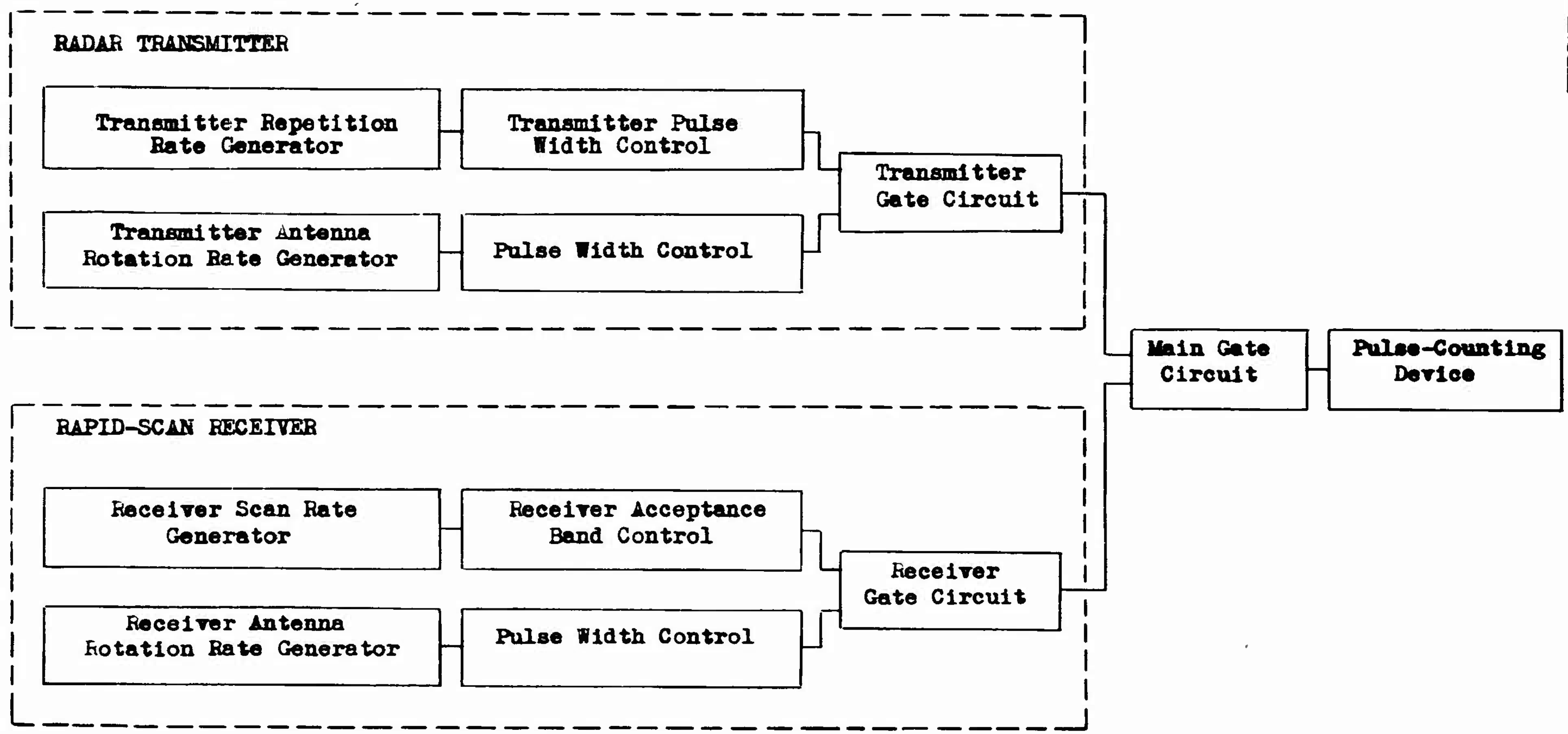

FIGURE NO. 1

BLOCK DIAGRAM OF SIMULATOR

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time may be varied, thus allowing variation of the transmitter's pulse width. This latter circuit therefore delivers pulses of repetition rates variable from 500 to 2500 pps and widths variable in the neighborhood of 5 μs.[2]

A circuit producing trigger pulses of very low frequency simulates the antenna rotation rate of the radar transmitter. These pulses trigger a monostable multivibrator whose delay time is adjustable. Thus, this circuit also delivers a pulse output of variable repetition rate and width. Since this pulse width, and the antenna rotation rate and beam width are related by the equation

$$\text{Pulse Width} = \frac{\text{Antenna Beam Width}}{\text{Antenna Rotation Rate}},$$

the two transmitter antenna parameters of rotation rate and beam width are determined by the settings of these two multivibrator circuits. Combinations of these settings allow variation of antenna rotation rate from 2 to 20 revolutions per minute and variation of beam width from 1 to 20 degrees.

The simulated radar transmitter pulse and transmitter antenna parameters are fed into a gate circuit which produces an output pulse only when its two input triggers arrive

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[2] Actually, radar pulse width was not varied. Pulse width is of minor importance unless receiver scan rates are so high that the period in any one scan in which the receiver can receive a transmission approaches the pulse width. Such scan rates were not evaluated in this project.

simultaneously. The width of the gate output pulse is equal to the time during which the two input pulses are in coincidence. Thus the gate circuit output consists of discrete groups of pulses, simulating the transmission which is available for interception by the receiver during the times the radar transmitter antenna is directed toward the receiver (i.e., the radar looks).

The simulated rapid-scan receiver consists of an arrangement basically similar to that described for the radar transmitter. Scan rate is simulated by an astable multivibrator, the output pulses of which represent the acceptance band of the receiver. Scan rate is controllable from 20 cps to 10,000 cps and the ratio[3]

$$\frac{\text{Acceptance Band}}{\text{Total Scanned Band}},$$

the other important parameter of the receiver, is also variable.

Receiver antenna parameters of rotation rate and beam width are simulated by circuits identical in type to those of the transmitter antenna. Rotation rate is variable from 10 to 300 revolutions per minute and beam width from 5 to 60 degrees.

The simulated receiver operation and receiver antenna

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[3] Matthews, op. cit. This ratio is the quantity α_r in Matthews' report.

parameters are combined in the receiver gate circuit, producing an output simulating the entire operation of the rapid-scan receiver. This is a series of discrete groups of pulses similar in form to the output of the transmitter gate circuit. A single group designates the time the receiver antenna is directed toward the transmitter with the receiver correctly tuned and thus receptive to radar transmission.

It remains to determine the operation of the rapid-scan receiver on the radar's transmission and its effectiveness in the interception of that transmission. This is done by combining the transmitter and receiver information in the main gate circuit from which an output will appear only when a pulse from the radar transmitter arrives at the receiver at such a time as to be intercepted within the acceptance band of the receiver. The number of these pulses intercepted is then indicated directly by the pulse-counting device, as a function of all the parameters of both the transmitter and receiver systems.

For the problem in which the receiver antenna is considered to be omnidirectional, the circuit simulating receiver antenna parameters is disabled.

A photograph of the simulator and its power supply is shown in Figure No. 2.

In the recording of data for any given run, values of all parameters specifying the particular set of conditions for

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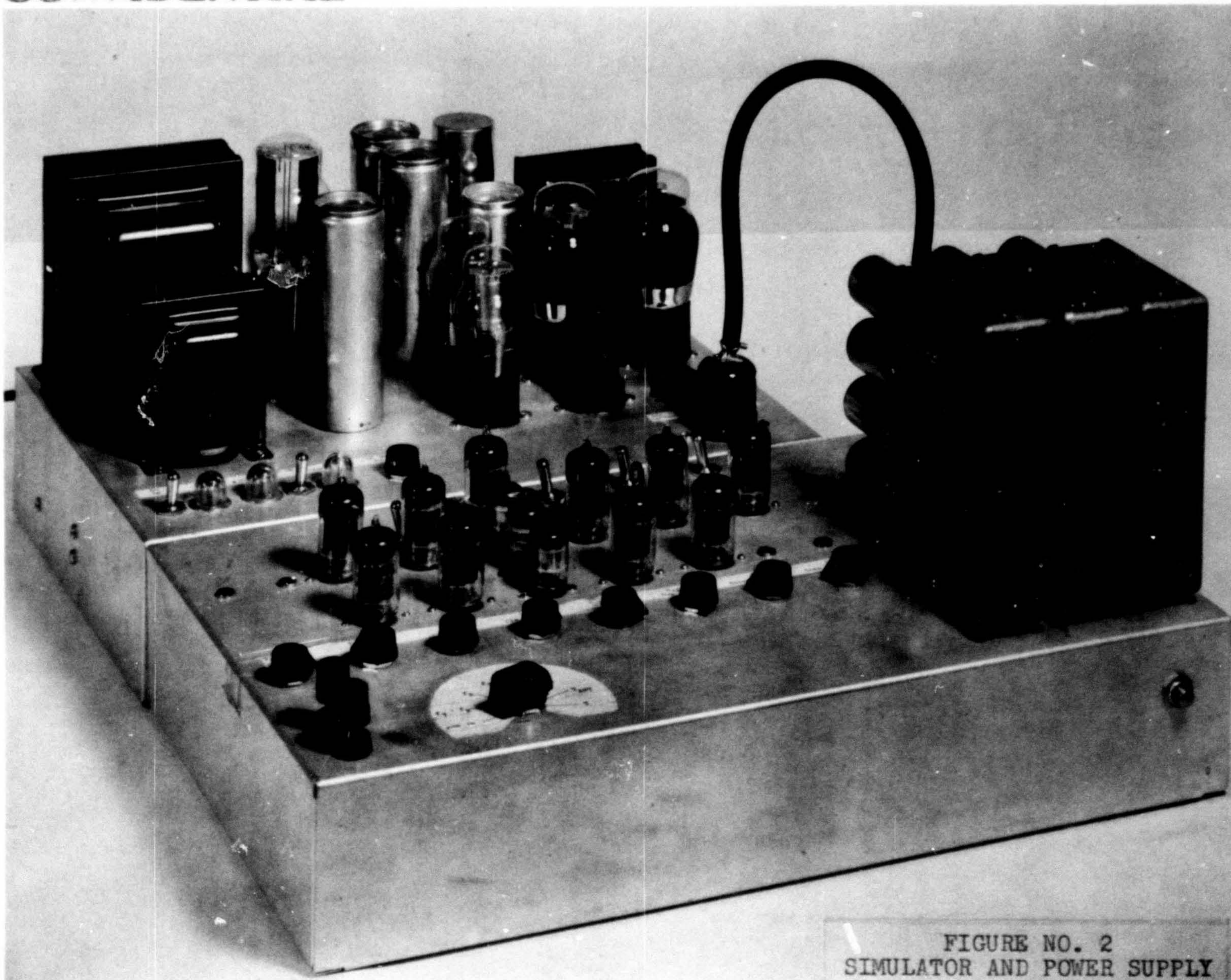

FIGURE NO. 2
SIMULATOR AND POWER SUPPLY

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that run were set by adjustment of the simulator's control potentiometers. Measurement of these values was accomplished by viewing on an oscilloscope the pulse waveforms throughout the circuit. Output information provided by the readings of the decade counter units was then recorded. This information was in the form of numbers of counted pulses, representing the simulated interception of radar transmitter pulses by the intercept receiver at the moment the radar transmitter antenna was directed toward the receiver.

It was found that a minimum of one hundred trials in any given run was required to insure a satisfactory statistical sample. Consequently, every run was composed of at least one hundred trials (with each trial corresponding to a radar look).

CHAPTER III

INTERCEPT PROBABILITY WITH RAPID-SCAN RECEIVERS: A DISCUSSION OF RESULTS

A. Omnidirectional Case

In this case the receiver was assumed to employ an omnidirectional receiving antenna. In this condition, there exists the possibility of the receiver obtaining an intercept every time the rotating radar transmitter antenna is directed toward the receiver, that is, on every radar look.

A.1 General Relations

The following general statements apply to a long-term situation - the average of a statistical sample of radar looks. The number of pulses intercepted from any one radar look (and, indeed, the probability of intercepting any individual look at all) is controlled partly by additional relationships discussed subsequently.

It was found that THE INTERCEPTED PERCENTAGE OF THE TOTAL NUMBER OF RADAR PULSES AVAILABLE TO THE RECEIVER IS INDEPENDENT OF RECEIVER SCAN RATE. This is illustrated by the family of curves shown in Figure No. 3.

It was further found that THE INTERCEPTED PERCENTAGE OF THE TOTAL NUMBER OF RADAR PULSES AVAILABLE TO THE RECEIVER IS

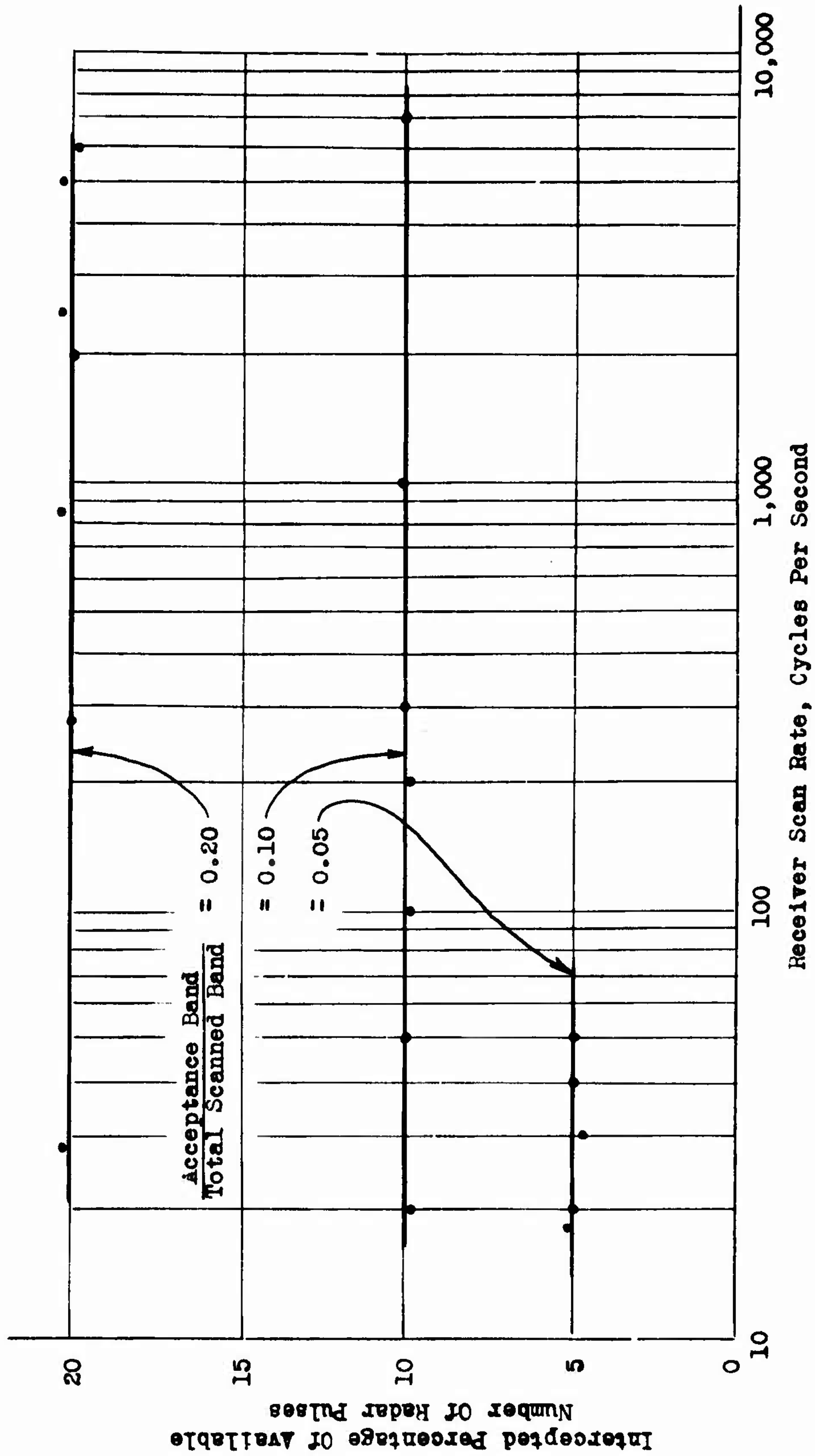

FIGURE NO. 3

INTERCEPTED PERCENTAGE OF AVAILABLE RADAR PULSES vs. RECEIVER SCAN RATE

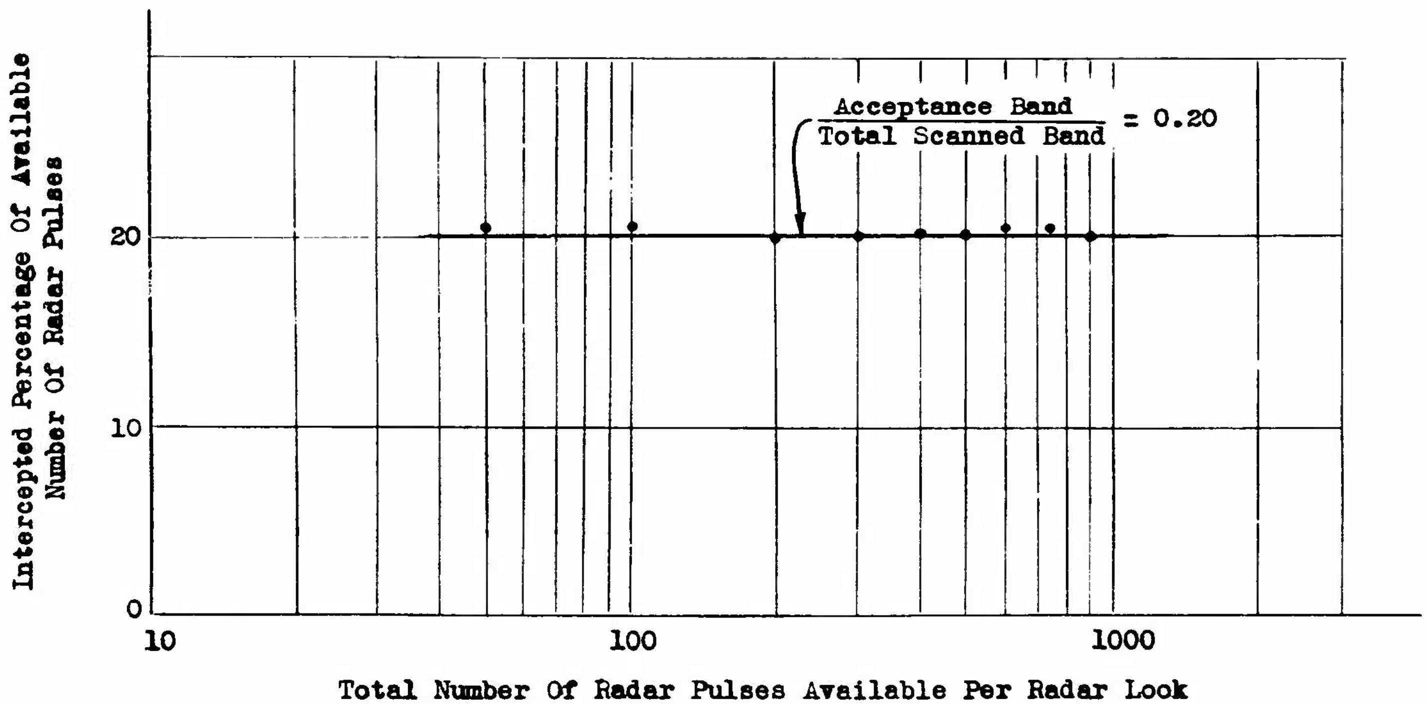

FIGURE NO. 4

INTERCEPTED PERCENTAGE OF AVAILABLE RADAR PULSES vs. TOTAL NUMBER OF AVAILABLE RADAR PULSES

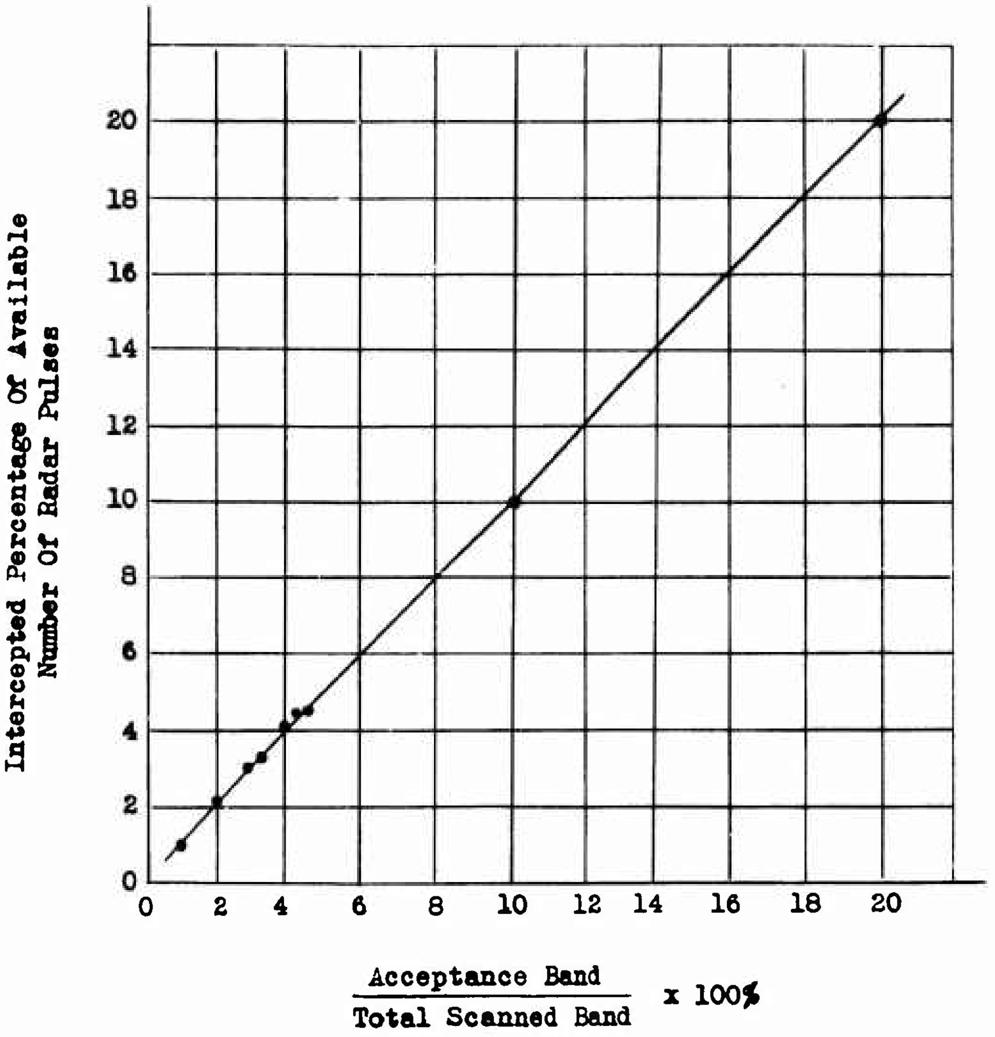

FIGURE NO. 5

INTERCEPTED PERCENTAGE OF AVAILABLE RADAR PULSES vs. RATIO OF RECEIVER ACCEPTANCE BAND TO TOTAL SCANNED BAND

INDEPENDENT OF THE TOTAL NUMBER OF AVAILABLE RADAR PULSES. This is illustrated by the curve shown in Figure No. 4.

It was also found that THE INTERCEPTED PERCENTAGE OF THE TOTAL NUMBER OF RADAR PULSES AVAILABLE TO THE RECEIVER IS DEPENDENT ONLY UPON, AND IS EQUAL TO, THE VALUE OF THE RATIO,

$$\frac{\text{ACCEPTANCE BAND (FREQUENCY)}}{\text{TOTAL SCANNED BAND (FREQUENCY)}} \times 100 .$$

This is illustrated by the curve of Figure No. 5.

The ratio, $\frac{\text{Acceptance Band}}{\text{Total Scanned Band}}$, is a known constant of the intercept receiver. Therefore, it may be stated that, for any given intercept receiver employing an omnidirectional receiving antenna, $\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} \times 100\%$ of whatever quantity of pulses being radiated by the radar transmitter will be intercepted.

A.2 Synchronism Between Radar And Receiver

When the receiver scan rate period is an exact multiple or sub-multiple of the pulse period of the radar transmitter, synchronism will exist between the radar transmitter and intercept receiver. Under this condition, it is possible that no intercepts will be obtained, or that many more than the expected percentage will be obtained from any one radar look. If the receiver scan rate period is an exact multiple of the radar's pulse period, the probability exists of intercepting a quantity of radar pulses equal to the number of scans that the receiver makes during one radar look. If the receiver scan rate period

is an exact sub-multiple, it could happen that all radar pulses transmitted during a radar look would be intercepted.

The possibility of such synchronism, however, does not violate the statement predicting the percentage intercepted to be the ratio, $\frac{\text{Acceptance Band}}{\text{Total Scanned Band}}$. This is due to the fact that in practical equipment, there will be enough random drift of the scanning frequency oscillator in the receiver (and in some cases, of the radar's pulse repetition rate) to prevent prolonged synchronism. Hence, in any practical case of synchronism, there may be times of no interceptions and other times of interceptions in excess of the predicted percentage. The important fact is that, over a sufficiently long period of time, the number of pulses intercepted is found to be the percentage, $\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} \times 100$. This phenomenon of random drift preventing prolonged exact synchronism was observed in the operation of the simulator, which employed a typical receiver scan circuit.

A.3 Effect of Very Long Scan Rate Period

A second condition in which no intercepts might be obtained exists when the receiver scan rate period is greater than the time the radar transmitter antenna is directed toward the receiver. Under this condition, it is possible for this time to fall between the times of occurrence of the acceptance period in the receiver. When this occurs, no radar pulses will be intercepted on some radar looks. On other radar looks, an acceptance period or fraction thereof will occur during the radar look. It is not necessary that there be synchronism between

radar antenna rotation and receiver scan rate for this condition to occur. However, in considering the additional effect of this type of synchronism, it can be said that since prolonged exact synchronism between the radar antenna rotation and the receiver scan rate is likewise unlikely (again, for the reasons of random drift), there will not be continuous interception of the same number of pulses, or no pulses, on many successive radar looks. Here again, over a sufficiently long period of time, the number of radar pulses intercepted is found to be the percentage, $\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} \times 100$.

A.4 Effects of Jittered Scan Rate To Alleviate Synchronism

No extensive effort has been made here to evaluate the precise quantitative effects of synchronism other than to demonstrate its existence. A very effective technique which may be employed to alleviate the possible effects of synchronism involves the introduction of "jitter" in the intercept receiver scan rate.[1] This is generally possible in any intercept system capable of scanning at high rates (where an electronic tuning process is normally involved).

In the practical case, a jittered receiver scan rate can largely nullify the objectionable effects of synchronism, namely, the possibility of intercepting no radar pulses from a

[1] "Jitter" here refers to variation of receiver scan rate at some desired rate.

particular radar look. Introduction of jitter was investigated experimentally and typical data are graphically illustrated in Figure No. 6(a) and Figure No. 6(b). In these figures, the number of radar pulses intercepted on successive radar looks is given, the points on the horizontal time axis representing the occurrence of successive radar looks. For this case, the multivibrator circuit simulating radar transmitter pulse repetition rate and the multivibrator circuit simulating intercept receiver scan rate were each controlled by separate, stable audio oscillators. By means of a third audio oscillator, receiver scan rate could be varied at the desired jitter rate. With transmitter pulse repetition rate and receiver scan rate each set very near 1000 cps to produce synchronism, and without jitter, Figure No. 6(a) shows that it was possible for the receiver to intercept no radar pulses for a period of several successive radar looks.[2] However, on those looks when interceptions were made, the number of pulses intercepted was usually a large fraction of the total number available per radar look. For the same conditions of transmitter pulse repetition rate and

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[2] For example, in the center of the figure, 13 successive radar looks occurred during which no interceptions were made. As the radar antenna rotation period was 4 seconds, this interval amounted to 42 seconds. Many search radars utilize slower antenna rotation rates (than that in this example) with periods of the order of 10 seconds; for such radars, this no-interception period (time interval before an intercept is obtained) would be 130 seconds, or over two minutes. This would be in excess of an "operationally short time" in a number of circumstances.

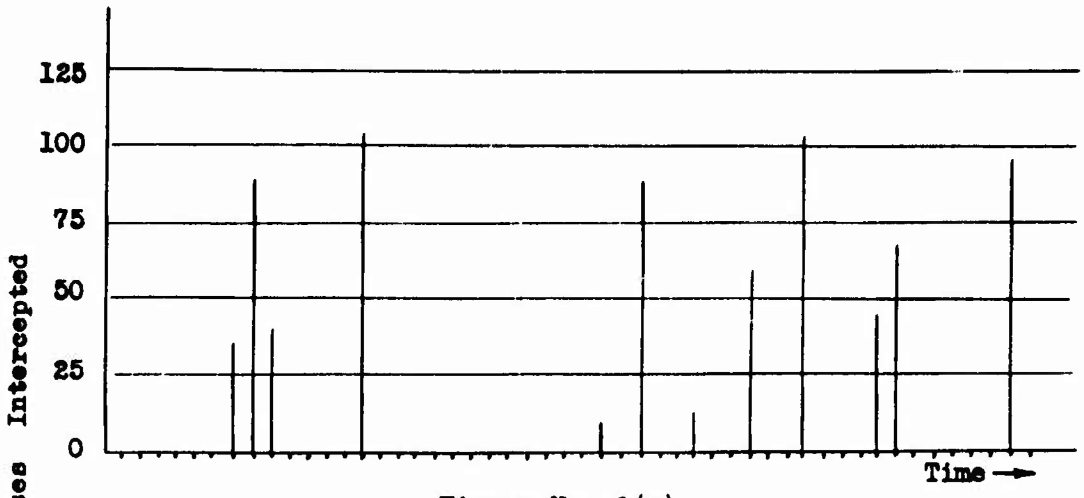

Figure No. 6(a)
No Jitter

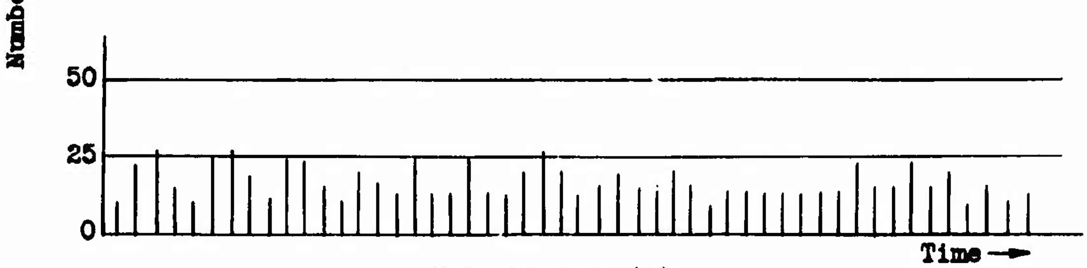

Figure No. 6(b)
10 cps Jitter (10% Deviation In Scan Rate)

Data:

Radar Transmitter PRR $\approx$ 1000 pps.
Radar Transmitter Antenna Period = 4 sec.
Number Of Available Radar Pulses Per Radar Look = 151
Receiver Scan Rate $\approx$ 1000 cps.

$$\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} = 10\ \%$$

FIGURE NO. 6

DATA ON EFFECT OF INTRODUCTION OF
JITTER IN RECEIVER SCAN RATE

average receiver scan rate, but with the introduction of scan rate jitter (continuous variation of scan rate between 1120 cps and 915 cps) at a 10 cps rate, Figure No. 6(b) shows the number of pulses intercepted to be generally less per radar look than in the case of no jitter, but that interception of radar pulses occurred on every radar look. In both cases, the long-term average percentage of pulses intercepted out of the total number available was the same, i.e., 10%, as predicted by the ratio of receiver acceptance band to total scanned band. It is thus seen that the introduction of even this simple form of scan rate jitter largely eliminated the undesirable aspect of synchronism. In an operational sense, the interception of pulses from each radar look is a desirable goal of the intercept operation.

In most cases, the probability of synchronism is very low. It was found that only a small difference between radar transmitter pulse repetition rate and receiver scan rate (transmitter pulse repetition rate at 1010 cps and receiver scan rate at 1020 cps; a difference of approximately 1%) was necessary to eliminate the practical effects of synchronism.

A.5 General Recommendations Based on Omnidirectional Case

When the several conditions outlined in the preceding paragraphs are examined relative to practical system parameters, it is found that a wide latitude in receiver scan rate selection

is possible provided the ratio of receiver acceptance band to total scanned band is not too small (Section A.1). A lower limit on receiver scan rate is set by the requirement that the scan period be less than the time that a typical rotating radar antenna is directed toward the receiver (Section A.3). A wide range of higher scan rates is possible, it being remembered that the phenomenon of synchronism is possible if receiver scan rate and radar transmitter pulse repetition rate are integrally related[3] (Section A.2). Between these limits there exists a receiver scan rate region (20-30 cps) of considerable practical importance. This range is above the desirable lower limit and below the region of complete synchronism, for the time interval during which the receiver is sensitive to a particular frequency is in excess of the pulse period of most existing radars. Thus, in this scan rate region, an interception of some radar pulses will occur on each radar look. A further practical aspect is that these relatively low receiver scan rates can be achieved by mechanical as well as electronic tuning techniques.

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[3]Very high receiver scan rates can be visualized in which the total scanned band is scanned in the duration of a typical radar pulse. This is attractive from the intercept probability standpoint because a portion of every available radar pulse would be intercepted. Unfortunately, display problems for such a system are severe, as are also the circuit bandwidth requirements set by the very narrow "chopped" pulses. The total intercepted energy for such a system is still given by the ratio of receiver acceptance band to total scanned band.

B. Directional Case

In this case, the receiver was assumed to employ a rotating directional antenna for the purpose of establishing bearing to the radar transmitter from the intercept receiver. The possibility of obtaining an intercept then exists only during a time coincidence between a radar look and the interval during which the directional receiving antenna is directed toward the radar transmitter.

B.1 General Relations

As in the omnidirectional case, it was found that THE INTERCEPTED PERCENTAGE OF THE TOTAL NUMBER OF RADAR PULSES AVAILABLE TO THE RECEIVER IS INDEPENDENT OF BOTH RECEIVER SCAN RATE AND TOTAL NUMBER OF AVAILABLE RADAR PULSES.

It was further found that THE INTERCEPTED PERCENTAGE OF THE TOTAL NUMBER OF RADAR PULSES AVAILABLE TO THE RECEIVER IS DEPENDENT ONLY UPON, AND IS EQUAL TO, THE VALUE OF THE EXPRESSION,

$$\left[\frac{\text{RECEIVER ANTENNA BEAM WIDTH (DEGREES)}}{360^\circ}\right]\left[\frac{\text{ACCEPTANCE BAND (FREQ.)}}{\text{TOTAL SCANNED BAND (FREQ.)}}\right] \times 100 .$$

It is seen that there exists a similarity to the omnidirectional case, except for the additional multiplying factor of

$$\frac{\text{Receiver Antenna Beam Width}}{360}.$$ [4] This

[4]Matthews, *Op. cit.* This ratio is the quantity β_r in Matthews' report.

factor is equivalent to the ratio of the time during which the directional receiving antenna is directed toward the radar transmitter to the time of one rotation period of the receiving antenna.[5] This is also a known constant of the directional receiving antenna. Therefore, it may be stated that for any given intercept receiver employing a directional receiving antenna, the percentage

$$\left[\frac{\text{Antenna Beam Width}}{360}\right] \left[\frac{\text{Acceptance Band}}{\text{Total Scanned Band}}\right] \times 100\%$$

of whatever quantity of pulses being radiated by the radar transmitter will be intercepted. As in the omnidirectional case, this statement is qualified only by the fact that it applies to interceptions made over a sufficiently long period of time to allow a satisfactory statistical sample; it is not strictly true for any one particular radar look.

---

[5]
$$\frac{\text{Time during which receiving antenna is directed toward radar}}{\text{Time of one rotation period of receiving antenna}} =$$

$$= \frac{\dfrac{\text{Antenna Beam Width (Degrees)}}{\left[\text{Antenna Rotation Rate (RPM)} \times 360/60\right] \text{(Degrees/Sec.)}}}{\dfrac{1}{\left[\text{Antenna Rotation Rate (RPM)} \times 1/60\right] \text{(Revolutions/Sec.)}}}$$

$$= \frac{\text{Antenna Beam Width}}{\text{Antenna Rotation Rate} \times 6} \times \frac{\text{Antenna Rotation Rate}}{60}$$

$$= \frac{\text{Antenna Beam Width}}{360}$$

B.2 Synchronism Between Radar and Receiver

The same statements concerning synchronism made for the omnidirectional case, (Chapter III, A.2), apply also for the directional case, except that the long-term average percentage of intercepted radar pulses will be controlled by the factor,

$$\left[\frac{\text{Antenna Beam Width}}{360}\right]\left[\frac{\text{Acceptance Band}}{\text{Total Scanned Band}}\right]$$

B.3 Effect of Very Long Scan Rate Period

The statements made in Chapter III, A.3 concerning the results of a receiver scan rate period long relative to the time of a radar look also apply here except that, again, the long-term average percentage of intercepted pulses will be based upon the factor mentioned in the preceding paragraph.

In essence, the addition of the third gate, the directional receiving antenna, reduces the intercept probability very greatly. Further, it reduces the number of intercepted pulses per radar look to the point that there is no guarantee in the practical case of intercepting a radar signal in anything approaching an operationally short time regardless of receiver scan rate. On first thought, it might appear that a solution would lie in increasing the rate of rotation of the directional receiving antenna to a point such that the period of this rotation would be less than the duration of a typical

radar look. (Doing this might also necessitate a considerable increase in receiver scan rate in order to insure an appreciable number of scans during the time the receiving antenna was directed toward the radar). This procedure would have the tendency to insure the interception of some radar pulses on every radar look. However, keeping in mind the pulse repetition rates of most existing radars, it is apparent that this procedure would reduce the time during which the receiving antenna is directed toward the radar to such a low value (relative to the pulse period of the radar) that only a fraction of a radar pulse might be intercepted, and oftentimes none would be intercepted.

B.4 Stopped-Scan Technique

Notwithstanding the serious reduction in the number of pulses intercepted as a result of the introduction of a directional receiving antenna, direction-finding is still an important phase of the intercept operation. One solution has been evaluated in this project.[6] The basic plan involves an initial search operation using an omnidirectional receiving antenna. Receiver scan rate and acceptance band are selected to insure a high intercept probability in accordance with the normal conditions for the omnidirectional case of interception.

---

[6] This idea, suggested by W. R. Rambo is currently being tested in a receiver at the Stanford Electronics Research Laboratory.

Upon the interception of a radar signal, the receiver scan is stopped on frequency for a short interval of time. This time interval lasts for the remainder of the radar look beyond the point in the look at which the first interception is made, or for a time sufficient to complete the direction-finding operation, whichever time is the shorter. It is limited in any event to a fraction of second. This stopped-scan control is accomplished electronically.

Using the stopped-scan technique, all pulses following the initial interception during any one radar look can be intercepted, the average intercepted percentage increasing very materially over the continuous scan case. In effect, this provides a longer period of time in which to complete the direction-finding operation with the system switched electronically to the rotating direction-finding antenna. An important aspect of the use of this technique is that, in the interval during which the receiver scan rate is stopped, there is assurance that two of the three conditions necessary for a successful direction-finding operation are satisfied; the radar is "looking" at the receiver, and the receiver is "on tune". Thus, the initial search in frequency (using the omnidirectional receiving antenna) is not impaired by the inclusion of the direction-finding antenna in the system and the probability of a successful direction-finding operation is materially improved.

Unlike the continuous-scan case, receiver scan rate is quite important in controlling the percentage of available radar pulses intercepted with this stopped-scan technique. This arises through the time distribution of intercepted pulses within the radar look. With the relatively low scan rates recommended for the omnidirectional case, a group of successive radar pulses is intercepted from each radar look. The group may fall anywhere within the pulse train representing the look but the average position of this group will occur slightly before the middle of the radar look period. Since all subsequent radar pulses (within that radar look) will be intercepted when the receiver scan is stopped, the average intercepted percentage will be a little more than 50%. (See Figure No. 7(a)). With appreciably higher scan rates, no more pulses would be intercepted in the normal continuous scan case, but those that would will not necessarily be consecutive and moreover, will normally be distributed throughout the radar look. With higher scan rates, then, the probability of intercepting at least one radar pulse early in the radar look is high. Consequently, with the inclusion of the stopped-scan operation, and a high normal scan rate, the average number of radar pulses intercepted will be quite high, in the neighborhood of 90%. See Figure No. 7(b).

In effect, this method of operation provides an interception approximating that which would occur if the receiver

Intercepted % = 64.3 %

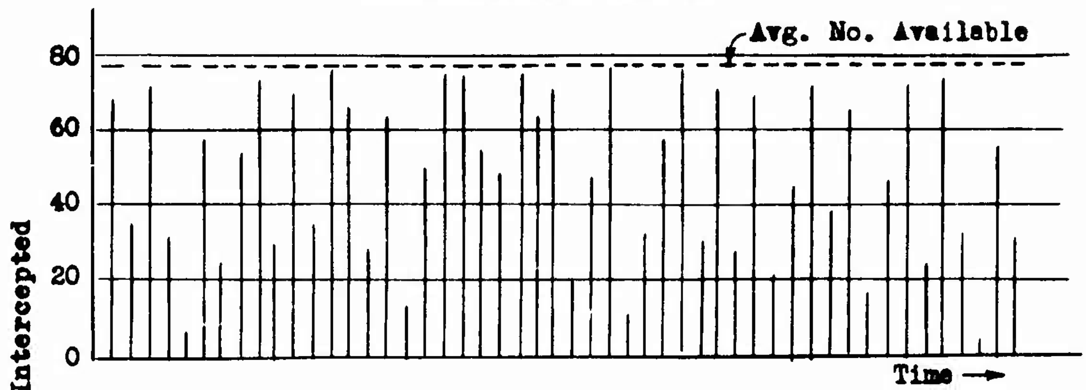


Figure No. 7(a)

Receiver Scan Rate = 25 cps.

Intercepted % = 94.3 %

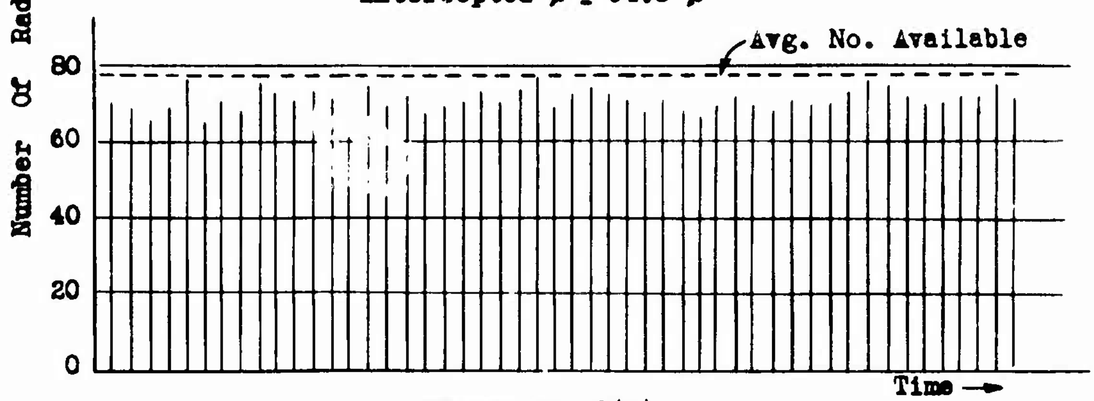


Figure No. 7(b)

Receiver Scan Rate = 250 cps.

Data:

Stopped-Scan Operation.
Omnidirectional Antenna Assumed.
Transmitter PRR = 1000 pps.
Radar Look = 0.04 sec.
Number Of Available Radar Pulses Per Radar Look = 77.

$$\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} = 10\ \%$$

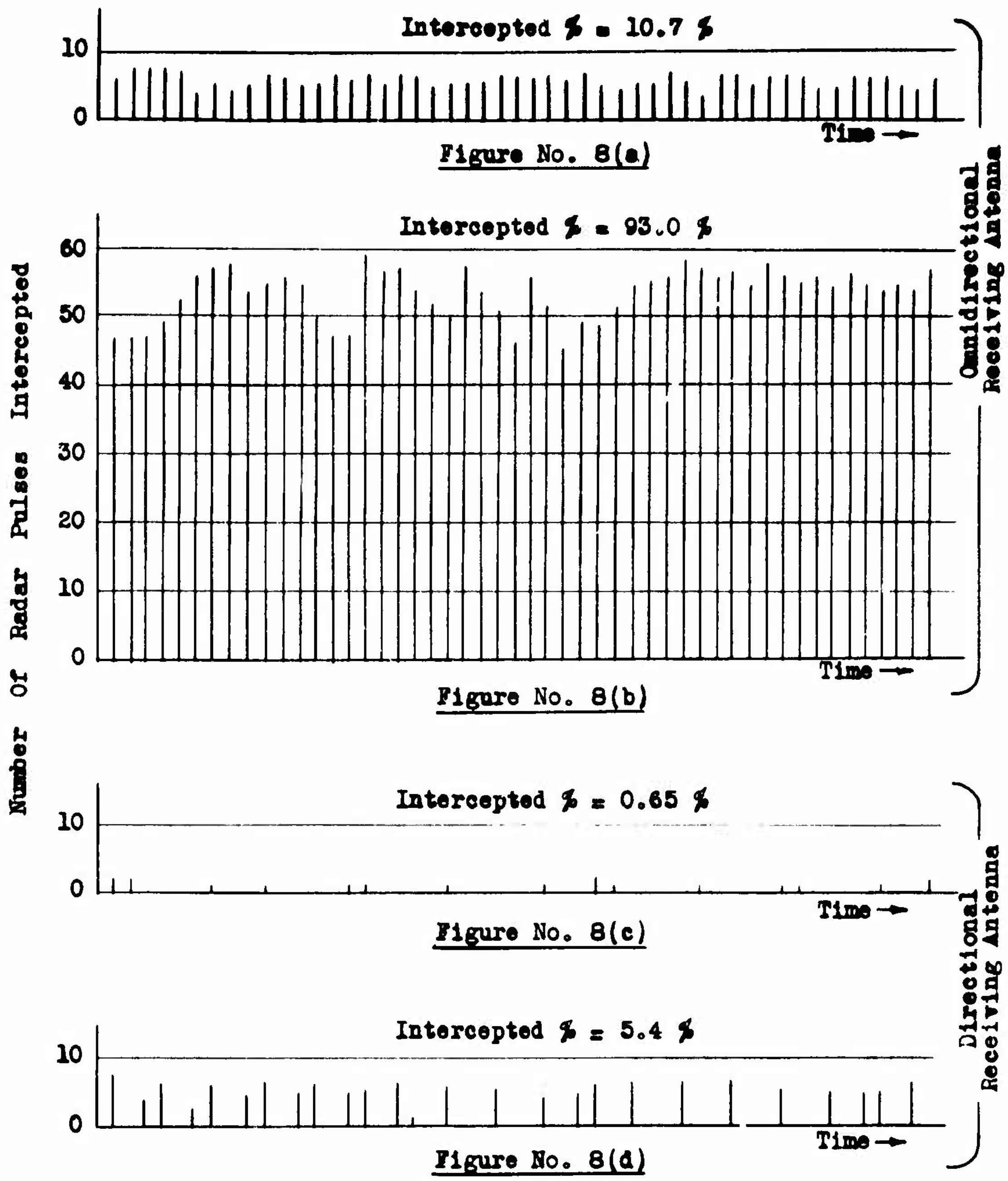
FIGURE NO. 7

DATA ON EFFECT OF INCREASING RECEIVER SCAN RATE IN CONJUNCTION WITH USE OF STOPPED-SCAN OPERATION

were tuned continuously to the signal frequency, that is, if the receiver were not scanning. In addition, the continuous monitoring of the total rf spectrum being scanned by the receiver is carried out in the interval between radar looks with remarkably little loss in efficiency due to the low duty cycle of the radar look.

B.5 Direction-Finding Based on the Stopped-Scan Technique

The quantitative effects on direction-finding of the stopped-scan operation were investigated experimentally by incorporating appropriate modifications in the receiver circuits of the simulator. Typical data of the experiment are illustrated graphically in Figure Nos. 8(a), 8(b), 8(c) and 8(d). In these figures, the number of radar pulses intercepted on successive radar looks is given, the points on the horizontal time axis representing the occurrence of successive radar looks. These figures are each part of the same run and are therefore plotted on the same sheet for comparison. For this run, the average number of radar pulses available per radar look was 58 pulses. Figure No. 8(a) shows the distribution of pulses on continuous scan with an omnidirectional receiving antenna; the long-term average percentage of pulses intercepted was 10.7%, in general agreement with a 10% setting of the ratio of acceptance band to total scanned band. Figure No. 8(b) shows



Data:

Transmitter PRR = 588 pps.
Transmitter Antenna Period = 4 sec.
Radar Look = 0.10 sec.
Receiver Scan Rate = 46 cps.
Receiver Antenna Rotation Rate = 300 rpm.
Receiver Antenna Beam Width = 20°
Number Of Available Radar Pulses Per Radar Look = 58
$\frac{\text{Acceptance Band}}{\text{Total Scanned Band}} = 10\ \%$

FIGURE NO. 8

DATA ON EFFECT OF INTRODUCTION OF STOPPED-SCAN OPERATION

the distribution of pulses intercepted when stopped-scan was used with the omnidirectional receiving antenna; the long-term average intercepted percentage here was 93%, a considerable increase over Figure No. 8(a). Figure No. 8(c) shows the distribution of pulses intercepted on continuous scan with a directional receiving antenna; the long-term average intercepted percentage was 0.65%, in general agreement with the factor.[7]

$$\left[\frac{\text{Antenna Beam Width}}{360}\right]\left[\frac{\text{Acceptance Band}}{\text{Total Scanned Band}}\right] =$$

$$20/360 \times 0.10 \times 100\% = 0.56\%$$

Figure No. 8(d) shows the distribution of pulses intercepted when stopped-scan operation was used with the directional receiving antenna; the long-term average intercepted percentage was 5.4%, almost a ten-fold increase over Figure No. 8(c). The larger number of pulses intercepted per look aids the definition on a visual display of the antenna pattern and improves df accuracy thereby.

For the direction-finding cases of Figure Nos. 8(c) and 8(d), a second important aspect is the fact that the number of

[7]The receiving antenna was assumed to rotate at 300 RPM and to have a beam width of 20 degrees, these characteristics being representative of one conventional direction-finding antenna system.

radar looks during which no interceptions were made was reduced by one-third in the case where stopped-scan was used. (Compare Figure No. 8(d) with Figure No. 8(c)).

Further tests showed this effect to be a function of the duration of the radar look relative to the rotational period of the direction-finding antenna. With very short radar looks (in the order of 0.04 seconds), there was little increase in the number of direction-finding interceptions made with stopped-scan operation, but a very material improvement was observed as the duration of the radar look approached the rotational period of the direction-finding antenna. For example, as the duration of the radar look was increased from 0.10 second (the example plotted in Figure Nos. 8(a), 8(b), 8(c) and 8(d)) to 0.20 second, stopped-scan operation employed with the directional receiving antenna completely eliminated the phenomenon of no interceptions being made from a particular radar look.

CHAPTER IV

SUMMARY

Intercept probability has been investigated experimentally with emphasis on the problem as encountered in rapid-scan intercept receivers. The results obtained are general in nature and apply in many cases to either rapid-scan or slow-scan systems. This investigation was carried out by simulating the problem with electronic equipment in a manner facilitating the rapid accumulation of data.

The investigation divided itself naturally into two separate phases: first, consideration was given to the basic intercept problem encountered in a receiver employing an omnidirectional receiving antenna; and second, consideration was given to the additional problems encountered in receivers using rotating directional receiving antennas. In both instances it was assumed that the receiver was not sufficiently sensitive to receive a substantial portion of radar antenna minor-lobe radiation. The radar antenna thus constitutes one effective "gate" limiting the probability of interception.

For the omnidirectional case, it was found that the intercepted percentage of the total number of radar pulses available to the receiver was independent of (1) receiver scan rate,

and (2) the total number of available radar pulses; and further, that this percentage was dependent only upon, and equal to, the value of the ratio,

$$\frac{\text{Receiver Acceptance Band (Frequency)}}{\text{Total Scanned Band (Frequency)}} \times 100 \quad .$$

This suggests that the receiver acceptance band should be made as large as selectivity requirements permit.

When the period of receiver scan rate is greater than the duration of a radar look (a relatively low scan rate), it is possible that no interceptions will be made from some radar looks. In a region of higher receiver scan rates, synchronism between radar transmitter pulse repetition rate and receiver scan rate is possible when these two quantities are integrally related. When such synchronism exists, it is again possible that no interceptions will be obtained from some radar looks. To insure interception of some radar pulses on every radar look, a desirable goal of the intercept operation, it was found that an intermediate range of receiver scan rates (20-30 scans per second) was attractive. If higher scan rates are desired (in the region where synchronism is possible), it was found that the introduction of jitter in the receiver scan rate (variation of receiver scan rate at some desirable rate) was effective in largely eliminating the objectionable effects of synchronism. In any event, the likelihood of prolonged synchronism is small in the practical case because of normal equipment instabilities.

For the case of a directional receiving antenna, it was found that, again, the intercepted percentage of the total number of radar pulses available to the receiver was independent of receiver scan rate and total number of available radar pulses. This percentage proved to be dependent only upon, and equal to, the value of the expression,

$$\left[\frac{\text{Receiver Antenna Beam Width (Degrees)}}{360}\right]\left[\frac{\text{Receiver Acceptance Band (Frequency)}}{\text{Total Scanned Band (Frequency)}}\right] \times 100 \quad ;$$

Thus, the directional receiving antenna introduces a second fractional multiplier and it was found that, in many cases, intercept probability and the intercepted percentage of available radar pulses were reduced to such low values as to be of little or no significance from the operational standpoint. A method of increasing the duration of the average coincidence period (to facilitate a subsequent direction-finding operation) was evaluated. This involves an initial search using an omnidirectional antenna and stopping the receiver frequency scan (usually for the duration of the radar look) upon the interception of a radar signal. In several cases, it is an effective means for increasing the intercepted percentage of available radar pulses and for reducing the number of times the receiver (switched to a direction-finding antenna) obtains no interceptions from a particular radar look. By increasing receiver

scan rate to the order of 200 scans per second in conjunction with this "stopped-scan" technique, the intercepted percentage of available radar pulses could be increased to the order of 90%.

APPENDIX

DESCRIPTION OF EQUIPMENT

A. Simulator[1]

The circuit for the simulator consists essentially of multivibrator and gate circuits. Figure No. 9 illustrates the complete circuit diagram. Tubes V_{17}, V_{19}, and V_{21} are of the type 6AS6; all other tubes are of the type 12AU7. The astable multivibrator composed of V_1 and V_2 produces a trigger which simulates pulse repetition rate of the transmitter. This rate is controlled by potentiometer P_1. V_3 and V_4 comprise a monostable multivibrator which simulates transmitter pulse width. This pulse width is varied by potentiometer P_2.

Tubes V_5 and V_6, a combination of bootstrap circuit and blocking oscillator, produce a low frequency trigger to simulate transmitter antenna rotation rate (antenna sweep

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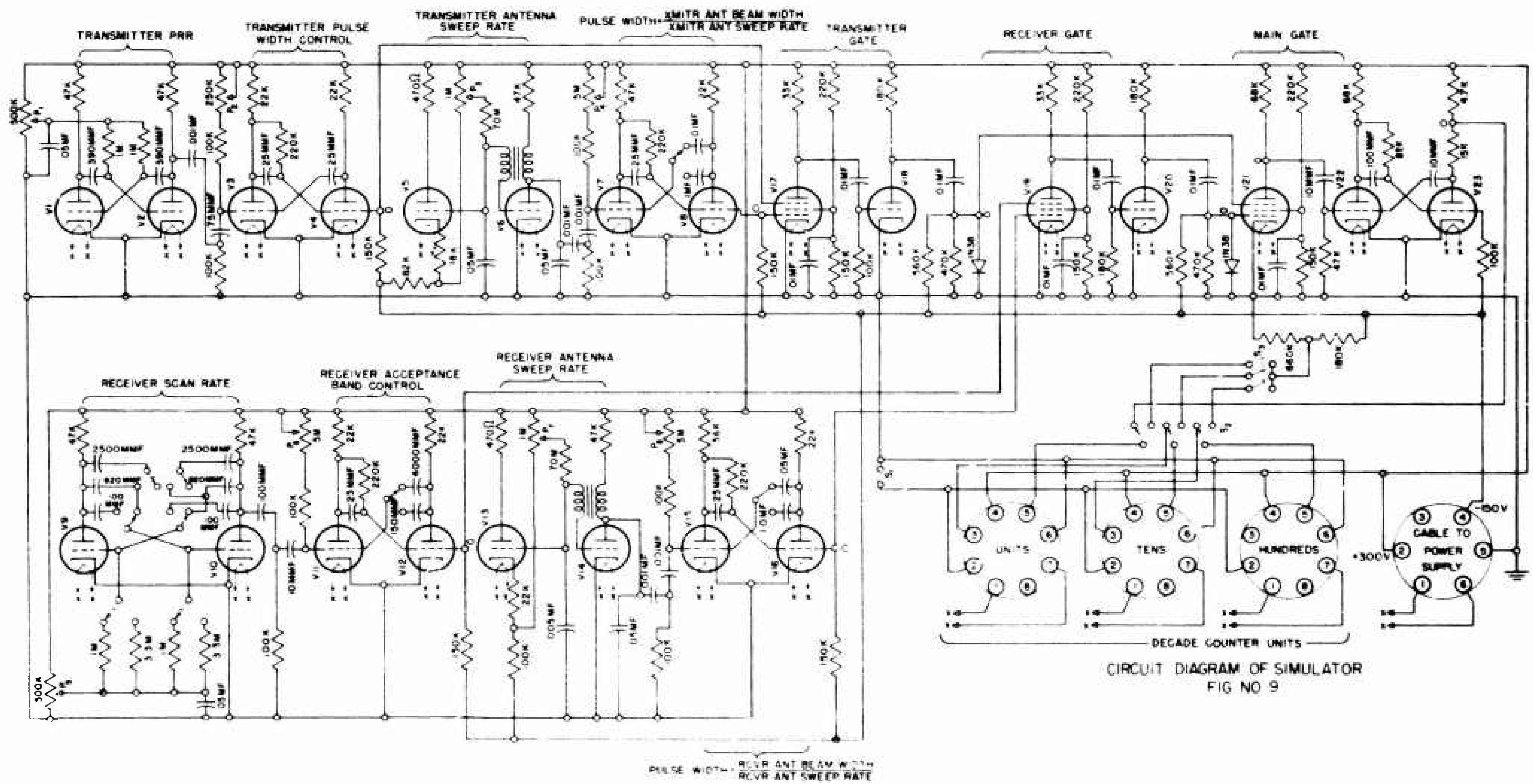
[1] In the design of this equipment, the following references were consulted:

Britton Chance, et al, Waveforms, M. I. T. Radiation Laboratory Series, Volume 19, First edition. McGraw-Hill, N. Y., 1949.

William C. Elmore and Matthew Sands, Electronic Experimental Techniques, National Nuclear Energy Series, Division V, Volume I. First edition. McGraw-Hill, N. Y., 1949.

Staff of M. I. T. Radar School, Principles of Radar, The Technology Press, Cambridge, Mass., 1944.



CIRCUIT DIAGRAM OF SIMULATOR
FIG NO 9

rate). The frequency of this trigger circuit is controlled by potentiometer P_3 and its period is of the order of several seconds. The output of this circuit triggers the monostable multivibrator composed of tubes V_7 and V_8, producing an output pulse which is controllable in width by potentiometer P_4. The output pulse width, transmitter antenna beam width, and transmitter antenna rotation rate are related by the equation,

$$\text{Output Pulse Width } (\mu s) = \frac{\text{Antenna Beam Width (Degrees)}}{\text{Antenna Rotation Rate (Degrees}/\mu s)}$$

Tubes V_9 and V_{10} comprise an astable multivibrator which produces a trigger simulating receiver scan rate. In any one range, this rate is controlled by potentiometer P_5. The output of this circuit triggers the monostable multivibrator composed of tubes V_{11} and V_{12}, producing an output pulse which simulates the acceptance band of the receiver. This pulse width is varied by potentiometer P_6. Receiver antenna rotation rate is simulated by the output of the circuit composed of tubes V_{13} and V_{14} and is controlled by potentiometer P_7. This circuit is of the same type as that of tubes V_5 and V_6. Its output triggers the monostable multivibrator comprised of tubes V_{15} and V_{16}, producing an output pulse whose width is varied by potentiometer P_8. This pulse width is related to receiver antenna beam width and receiver antenna rotation rate by

the same type of relation as that given for the transmitter.

The simulated transmitter pulse and transmitter antenna parameters, the output of tubes V_4 and V_8, respectively, are combined in the gate circuit of tube V_{17} to produce discrete groups of pulses which simulate the transmitter's entire transmission. These pulses are inverted in polarity by the tube V_{18} to give the desired form of input signal to the gate tube V_{21}.

In a similar manner, the receiver acceptance band pulse and receiver antenna parameters, the outputs of tubes V_{12} and V_{16}, respectively, are combined in the gate circuit of V_{19} to produce discrete groups of pulses which simulate the entire operation of the receiver. Polarity of these pulses is inverted in V_{20} to provide the proper input for V_{21}.

Finally, the simulated transmitter output and simulated receiver operation, the outputs of V_{18} and V_{20}, respectively, are combined in the gate circuit of tube V_{21}, producing an output simulating the operation of the rapid-scan receiver on the pulse transmission from the radar transmitter. This output triggers the monostable multivibrator consisting of tubes V_{22} and V_{23} to produce the proper form of input pulses for operation of the decade counter units. These units, arranged in a cascade of three to allow a total pulse count of one thousand, are each a Model 700 Berkeley Decimal Counting Unit, manufactured by the Berkeley Scientific Corporation.

S_1 is a normally-closed push-button switch which provides simultaneous resetting to zero of all counter units. Switches S_2 provide for the application of a -120 volt input test pulse through normally-open push-button switches S_3 to test for proper operation of the counter units.

The eight points marked "O" are oscilloscope monitoring points. Leads from each of these points to a rotary switch (not shown) allow the switching of an oscilloscope to any of these points for the purposes of monitoring and adjustment of the repetition rate, scan rate, pulse widths, etc.

The simulator was designed to cover the following ranges of the parameters:

Transmitter:

Pulse Repetition Rate: 500-2500 pps.
Pulse width : 5 µs
Antenna Rotation Rate: 2-20 rpm.
Antenna Beam Width: 1-20 degrees.

Receiver:

Scan Rate: 20 cps - 10 kc.
Acceptance Band: 0.1 - 0.2 scan rate period.
Antenna Rotation Rate: 10-300 rpm.
Antenna Beam Width: 5-60 degrees.

A photograph of the simulator and its power supply is shown in Figure No. 2.

B. Power Supply

The circuit diagram for the power supply is shown in Figure No. 10. The circuit is conventional and need not be described in detail. The supply provides regulated adjustable output of 0-350 volts, 0-140 ma., and a fixed negative voltage of 150 volts, 20 ma. A screwdriver adjustment allows internal impedance of the positive voltage source to be set to zero for satisfactory regulation of the output.

C. Auxiliary Equipment

Auxiliary equipment employed in this work included a Tektronix Type 514D Oscilloscope used for setting of transmitter repetition rate, receiver scan rate, and pulse widths; a Tektronix Type 512 Oscilloscope for setting the low-frequency parameters such as antenna rotation rates; and a Hewlett-Packard Model 410B vacuum tube voltmeter used for checking circuit voltages.

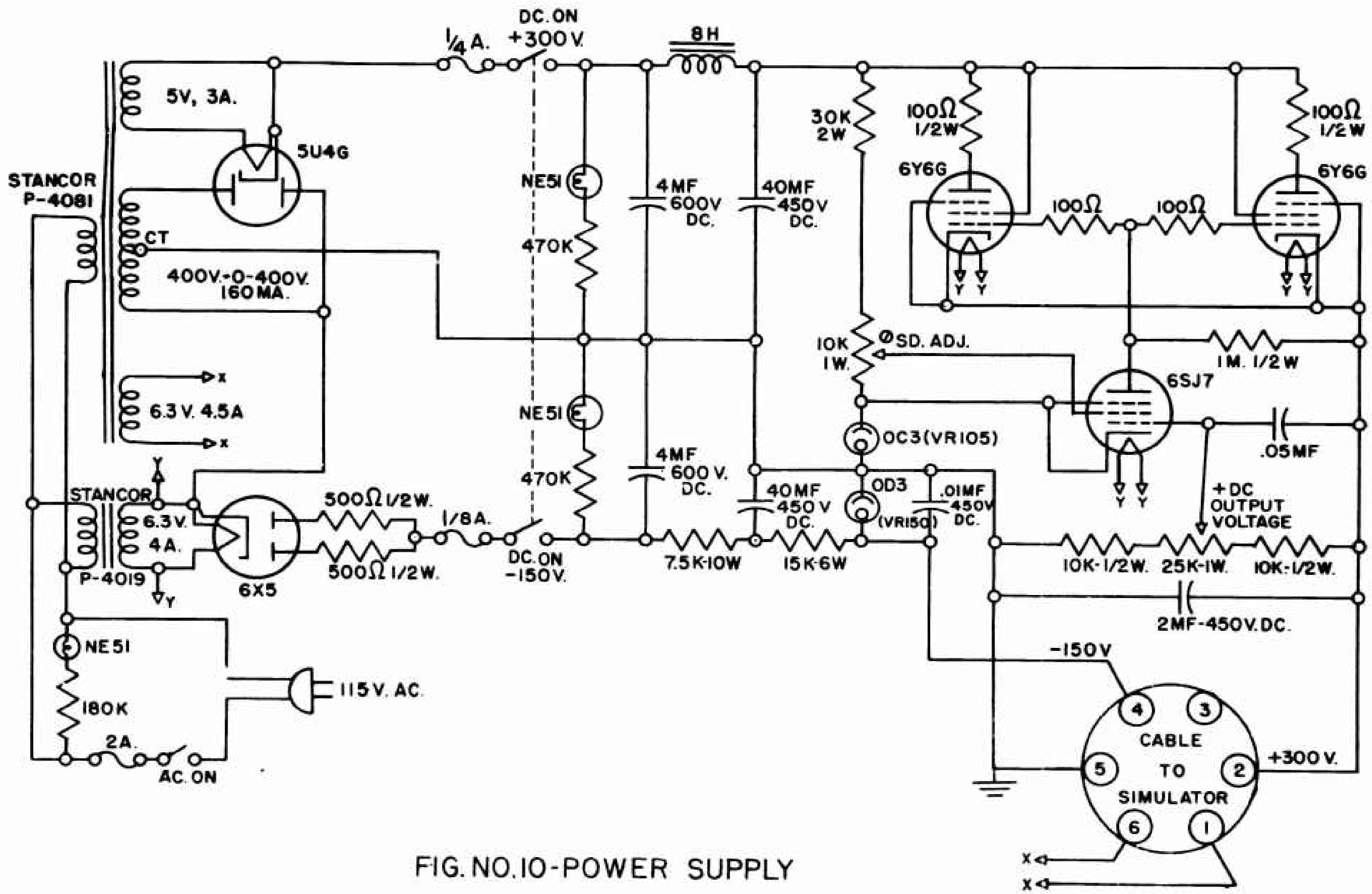


FIG. NO. 10-POWER SUPPLY

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Stanford University, Electronics Research Lab., Calif (Tech Report No. 13)
AN EXPERIMENTAL ANALYSIS OF SIGNAL INTERCEPTION BY RAPID SCAN MICROWAVE RECEIVERS - AND APPENDIX, by Douglas G. Dethlefsen. 1 June '52, 60 pp. incl. photo, diagrs, graphs.

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This report is concerned with an experimental evaluation of the probability of interception of a pulsed radar signal by periodically tuned intercept receivers. The problem has been attacked by simulating the radar transmitter and intercept receiver

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characteristics with electronic equipments providing pulse trains representing the time interval during which the radar transmission is directed toward the receiver, and the time interval during which an intercept receiver employing a directional receiving antenna is responsive to the incoming radar transmission. An interception of a radar transmission by the receiver is indicated by a finite time coincidence of these pulse trains. By a method of counting the pulses actually appearing in the simulated receiver circuits, the effectiveness of the operation is measured by determining both the time distribution and percentage of radar pulses intercepted.